

Challenging Pneumatic Requirements for Acoustic Testing of the Cryogenic Second Stage for the new Delta III Rocket

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ABSTRACT

The paper describes the unique pneumatic test requirements for the acoustic and shock separation testing of the Second Stage for the new Delta III Rocket at the Goddard Space Flight Center in Greenbelt, Maryland. The testing was conducted in the 45,000 ft³ (25-feet wide by 30-feet deep by 50-foot high) Acoustic Facility. The acoustic testing required that the liquid oxygen (LOX) and liquid hydrogen (LH₂) tanks be filled with enough liquid nitrogen (LN₂) to simulate launch fuel masses during testing. The challenge for this test dealt with designing, procuring, and fabricating the pneumatic supply systems for quick assembly while maintaining the purity requirements and minimizing costs.

The pneumatic systems were designed to fill and drain the both LOX and LH₂ tanks as well as to operate the fill/drain and vent valves for each of the tanks. The test criteria for the pneumatic sub-systems consisted of function, cleanliness, availability, and cost. The first criteria, function, required the tanks to be filled and drained in an efficient manner while preventing them from seeing pressures greater than 9 psig which would add a pressure cycle to the tank. An LN₂ tanker, borrowed from another NASA facility, served as the pre-cool and drain tanker. Pre-cooling the tanks allowed for more efficient and cost effective transfer from the LN₂ delivery tankers. Helium gas, supplied from a high purity tube trailer, was used to pressurize the vapor space above the LN₂ pushing it into the drain tanker. The tube trailer also supplied high pressure helium to the vehicle for valve control and component purges. Cleanliness was maintained by proper component selection, end-use particle filtration, and any on-site cleaning determined necessary by testing. In order to meet the availability / cost juggling act, products designed for LOX delivery systems were procured to ensure system compatibility while off the shelf valves and tubing designed for the semiconductor industry were procured for the gas systems.

INTRODUCTION

In the Spring of 1997, Goddard Space Flight Center (GSFC) and Mantech Systems Engineering Corporation (MSEC) met with Boeing (McDonnell Douglas at the time) to discuss the testing of the second stage of their new Delta III launch vehicle. Their testing required the use of Goddard's large, 45,000 ft³ Acoustic Facility to run qualification tests on the new second stage design.

Many challenges faced the combined test team such as obtaining a Space Act Agreement for doing a commercial test at a government facility, physically supporting and fitting the second stage into the acoustic cell, scheduling, designing and fabricating the cryogenic and pneumatic interfaces, and the time constraints. This paper addresses the cryogenic and pneumatic challenges that were encountered for this test.

What made the test unique was the requirement to simulate launch conditions in the LOX and LH₂ tanks using LN₂ as the working fluid during the acoustic and shock separation testing. Temporary, high purity storage and supply systems for LN₂ and helium were going to be needed to load and off-load almost 5000 gallons of LN₂ into the fuel tanks on the second stage. The following sections describe the design, fabrication, integration, testing, and performance of the cryogenic and pneumatic systems for the Delta III Second Stage Acoustic and Shock Separation tests conducted at Goddard Space Flight Center in February and March of 1998.

TEST CRITERIA

This test required the second stage be tested with the vehicle vertical, cryogenic temperature and mass in LOX and LH₂ tanks, control of second stage fill/drain and vent valves, and connections made using the vehicles umbilical panel. All components connected to the vehicles propulsion system were required to be suitable for LOX service.

The requirements for the LN₂ were that of Mil-P-27401C, grade B, Type I nitrogen with 100 micron absolute particle filtration. The GSE helium for the pneumatic valves was required to meet or exceed MIL-P-27407 with 25 micron absolute particle filtration supplied at a pressure of 650 psig. The LOX tank would require 3400 gallons of LN₂ to simulate the mass at launch and the LH₂ tank would require 1400 gallons. The Fill System was requested to fill the tanks in about 2 hours without exceeding one fourth of the tank burst pressure, thereby avoiding a pressure cycle on the tanks. The tanks were to be drained quickly without requiring a pressure cycle if possible.

DESIGN APPROACH

The approach that Goddard's Environmental Test Branch adopted was to assemble a team and assign a team leader during the proposal phase that would follow the test from proposal to completion. Preliminary designs were compiled in the proposal stage. Some of the early decisions evaluated LN₂ sources, LN₂ disposal, condensation of water, nitrogen versus helium for pushing LN₂ out of tanks, etc.. Detailed design and component selection could not happen until the Space Act Agreement was signed in October 1997.

The key to success in any design is obtaining correct, detailed information as early as possible in the design. This was accomplished by visiting the manufacturing plant to obtain dimensions, confirm orientations, and to discuss proposed design with those most familiar with the equipment. The detailed design started by developing a process and instrumentation (P&ID) drawing based on the Boeing test plan and sequence of operations. Component selection and procurement were based on function, availability and cost.

Conceptual Phase (Early Decisions)

Preliminary system design and analysis, meetings with the customer, and teamwork led to some effective decisions early in the project that proved instrumental in finishing under budget. Good analysis in the proposal (conceptual phase) provided a good foundation for the technical as well as the schedule and cost details. Some of the more critical decisions for this project are described below.

LN₂ Supply

No LN₂ taps existed in or near the acoustic facility. Piping from one of the existing tanks at our site would have required an LN₂ pump to provide the pressures and flow rates needed to fill the tanks. Temporary supply tanks with the capacity needed for this test would require concrete foundations in our parking lot area. Local gas suppliers were contacted and none of them had tankers we could park at our facility. Filling directly from delivery trucks was possible but the suppliers did not want the "used" LN₂ at the end of the test. Goddard team members networked and located portable LN₂ tankers at two other NASA centers that could be borrowed. The team pursued this option because it also provided a place to collect the LN₂ after the test.

LN₂ Disposal

Now that we had a vessel to drain the LN₂ into following a test, we had to determine what to do with the "used" LN₂. If the purity of the tanker was verified, then it was proposed that the "used" LN₂ be re-used to pre-cool the supply lines and second stage tanks for the next fill operation and use a delivery from our local supplier for topping off the tanks.

Helium Tanker

High pressure helium was required for the vehicles' pneumatic valves and low pressure helium gas was required for several GSE purges around the second stage. In addition, large volumes of gas were going to be required for pushing the LN₂ out of the second stage tanks. Because there was no requirement for gaseous nitrogen and helium does not collapse at LN₂ temperatures, helium was chosen early on as the gas used to push the LN₂ out of the LOX and LH₂ tanks. These factors drove the decision to use a tube trailer of high purity, high pressure helium and a manifold system that would be used for the vehicle valve control, vehicle purges, and tank draining.

Flex Lines

Flex lines were chosen for several reasons. The first being that they facilitate rapid integration of the second stage to a system that was installed prior to the start of the test. The second fundamental reason was that flex lines provide the isolation of the second stage from its' support fixture and from the building piping sysetms. The flex lines that were used had to be designed to dissipate electrical energy to eliminate any build up of static electricity. The disadvantages to using flex lines mostly revolved around the difficulty in cleaning convoluted shapes as well as greater pressure drops per foot of pipe.

P&ID Drawing

The Process and Instrumentation Diagram (P&ID) drawing was used to put the written requirements graphically onto paper detailing the piping systems as well as the instrumentation details. This was the tool used on this project to identify the components and the piping necessary to satisfy the Boeing test plan. The pipe sizes, component names, general relationships of equipment, etc. are portrayed in this fashion. A copy of the drawing is included at the end of this document.

Component Selection

Component selection followed after the start of the P&ID drawing but continued in a parallel effort as the design was finalized. Some of the components were to be used with LN₂ at cryogenic temperatures and some were to be used with high purity helium gas but all components were to be cleaned for oxygen service. This terminology, "cleaned for oxygen service," was found to mean many things to different suppliers. All of the components we purchased were tested either individually or as a system for total hydrocarbons measured as methane and for water contamination. The most difficult component to locate was the 100 micron absolute particle filter for cryogenic service at high flow rates and low pressure drops.

FABRICATION

Due to the use of flex lines, the external piping and the control console could be fabricated before the second stage had arrived at the test facilities. This design approach allowed for a smaller crew that could work sequentially through the task and thereby be dedicated to the task for its duration.

Purity Testing

The first step was to determine if the supplied components met the purity requirements. Those requirements are outlined below:

• H ₂ O, water vapor	< 11.5 ppm _v	per Mil-P-27401C, Grade B, Type I
• THC, Total hydrocarbon as methane	< 5.0 ppm _v	per Mil-P-27401C, Grade B, Type I
• NVR, Non-Volatile Residue	< 3.0 mg/ft ²	per Mil Std 1330, Oxygen Cleaning

The majority of the components met the requirements while several did not. Two different methods were used to test for purity. The first technique, an alcohol rinse of 1 square foot of surface area, was designed to sample for the non-volatile residue (NVR). The alcohol was evaporated at room temperature and then analyzed using an FTIR infrared spectrometer. The

second technique looks for contamination in the gaseous phase. A flame ionization detector (FID) was used to analyze for hydrocarbon contamination with sensitivity in the parts per billion (ppb) range and a hygrometer was used to analyze the water vapor contamination with sensitivity in the parts per billion (ppb) range.

Component Cleaning

The type of cleaning employed depended on the contamination that was found on the component. Hydrocarbon and particulate contamination was found in the 2-inch type L, ACR copper tubing used for the LN₂ lines. Alcohol soaked, lint-free, cleanroom wipes were attached to a ram and pushed through the lengths of copper until no evidence of contamination was visible. The line was then rinsed with alcohol and blown down with filtered nitrogen gas. The flex hoses procured with oxygen service cleaning showed hydrocarbon contamination. Flushing with isopropyl alcohol, followed by purging with dry nitrogen gas for 24-hours brought the tubing well within specification for both types of testing.

Develop Clean Brazing Technique

Since the inside of the copper tube could not be rinsed or cleaned after brazing, several brazing techniques were tried and evaluated to determine which would provide the better internal surface integrity. The standard technique used at our facility for cryogenic soldering of copper consists of using flux with the silver solder. This technique heavily oxidizes the internal surfaces. For more critical applications, the internal volume is purged with nitrogen gas while soldering. The concern was with the flux and any potential reactions with the nitrogen at the elevated temperatures of silver soldering. A technique was developed using a silver brazing alloy containing copper phosphorous that does not require flux since the flux gas created when heated etches the copper oxides and allows the silver solder to flow and bond with the copper. The internal surfaces were purged with argon gas while soldering and until the joint had cooled. This technique produced solder joints showing no traces of flux or oxidation and that met all the purity requirements with minimal gas purging.

Fabrication of Piping System

Upon arrival of the 4000 gallon LN₂ tanker borrowed from Marshall Space Flight Center, MSEC's Pressure Systems Recertification group evaluated the tanker and found it to meet the applicable codes. The tanker was then pressurized with high purity nitrogen gas and tested for THC and H₂O contamination. The installation of the LN₂ piping started with nitrogen purge maintained during the installation phase. Before opening the LN₂ tanker to the rest of the piping system, the LN₂ system piping was pressure tested per ANSI B31.3 and then certified for THC and H₂O contamination.

When ready, the 70,000 ft³ helium tube trailer was delivered. The delivered purity was 99.999% indicating that it had no more than 10 ppm_v of anything but helium. The tube trailer was sampled and tested for THC and H₂O contamination to baseline the source gas. High pressure helium was piped to the control console using stainless steel tubing and compression fittings. The helium system was pressure tested then certified for purity.

The control console contained all of the critical instrumentation. It was fabricated on the bench during periods of inclement weather. All connections to the console were via flex lines which allowed for easy positioning of the console for various operations.

SYSTEM INTEGRATION

The mobile support fixture (MSF) was sent ahead of the vehicle and was erected at our facility. After the fixture had been structurally tested, the interconnecting piping from the GSE flex line connection to the vehicle interface flex line was installed. This piping would allow for more rapid integration of the second stage to the GSE piping systems once installed in the acoustic facility.

Upon arrival of the second stage at Goddard, it was placed in the MSF. Some of the vehicle interface flex hoses were mated at the vehicle but capped until the rest of the system could be purged with helium. The site visit during the design phase was pivotal in ensuring all of the connections mated without any surprises. After the fixture was moved to the

acoustic cell, the control console and the LN_2 systems were connected to the piping on the MSF. The remainder of the vehicle connections were made after the piping systems had been purged and then leak tested up to the point of connection. The final connections were made and then the LOX and LH_2 tanks were leak tested and purge with helium.

SYSTEM PERFORMANCE

The filling, draining, and feedback systems performed as designed and met all of the customers' requirements. The calculated flowrates were achieved, the ability to control the ullage pressure in the tanks using helium was stable, and the amount of LN_2 consumed for each test was significantly reduced. In addition, the condensation of ambient water vapor on the uninsulated exterior surfaces of the tanks did not present the water problem anticipated when warming up the tanks.

LN_2 Filling / Draining

The use of the portable LN_2 tanker to pre-cool the supply lines, the LOX tank and the LH_2 tank worked well. Using the pressure building coil to build head pressure in the portable tanker allowed for flow rates around 50 gallons per minute (gpm). This technique allowed finer control when first introducing LN_2 into the tanks while trying to maintain LOX and LH_2 tank pressures less than 9 psig. We found that once, the bottom of the uninsulated tank was covered with LN_2 , that the flow rate could be throttled full open without causing the pressure to increase. Flow rates of up to 100 gpm were achieved when using the delivery trucks' high pressure LN_2 pumps. Fill times of 100 minutes were safely achieved.

Draining the LH_2 Tank worked very well using 8 psig of head pressure and gravity because the fill/drain connection was at the bottom of the tank. The LOX tank had to be drained through the fill line which enters the tank from the top and has a dip tube that extends to the bottom of the tank. At head pressures of 9 psig, the flow was estimated at 20 gpm. The decision reached was to drain the LOX tank using the design tank pressure which increased the flow to over 50 gpm. When the LOX tank reached gas break, the 4000 gallon fill/drain tanker was full. One of the unanticipated events was the time required (≈ 17 hours) to boil off the remaining LN_2 in the LOX tank even though it was an uninsulated aluminum vessel.

Level Sensing

Type 'T' thermocouples were taped to the aluminum surfaces of the tanks at their bottoms, middles, and tops. These thermocouples were a very effective and inexpensive way to indicate level in this application. The upper or top thermocouples were placed at the height on the tank calculated for the expected mass of LN_2 required. The measured amount of LN_2 pumped into each tank correlated very closely to the expected amount when the thermocouple indicated that LN_2 was at the appropriate level.

CONCLUSIONS

Forming a good team in the early phases of a test in order to identify and understand the test criteria was the key element to adhering to the fundamentals of the proposal and maintaining both the schedule and cost constraints. Taking the time in the beginning to design the system to meet the criteria led to some decisions that formed the basis of the final system. One of the design highlights that saved fabrication costs and integration time was the use of flex lines at optimum locations so that large sections of piping could be fabricated and tested independent of whether some other phase of the task was on schedule. The use and re-use of the LN_2 from the fill drain tanker proved to be beneficial in several ways. It was used to pre-cool the LN_2 lines and vehicle tanks while maintaining low pressures during initial cool down of the tanks. Re-using the LN_2 saved not only consumable costs but also solved the problem of where to dispose the LN_2 following a test.

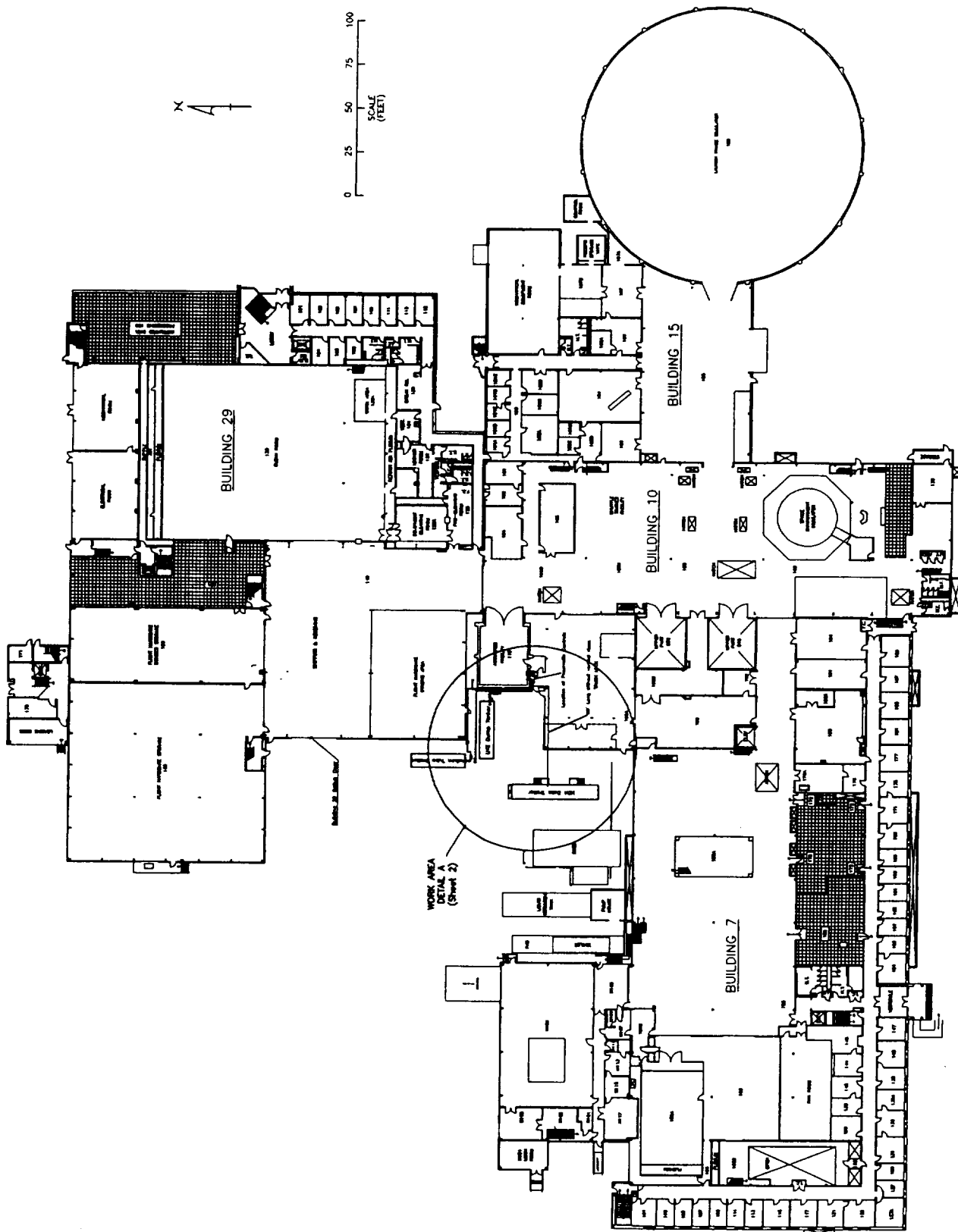


Figure 1: Goddard Space Flight Center Environmental Test Complex

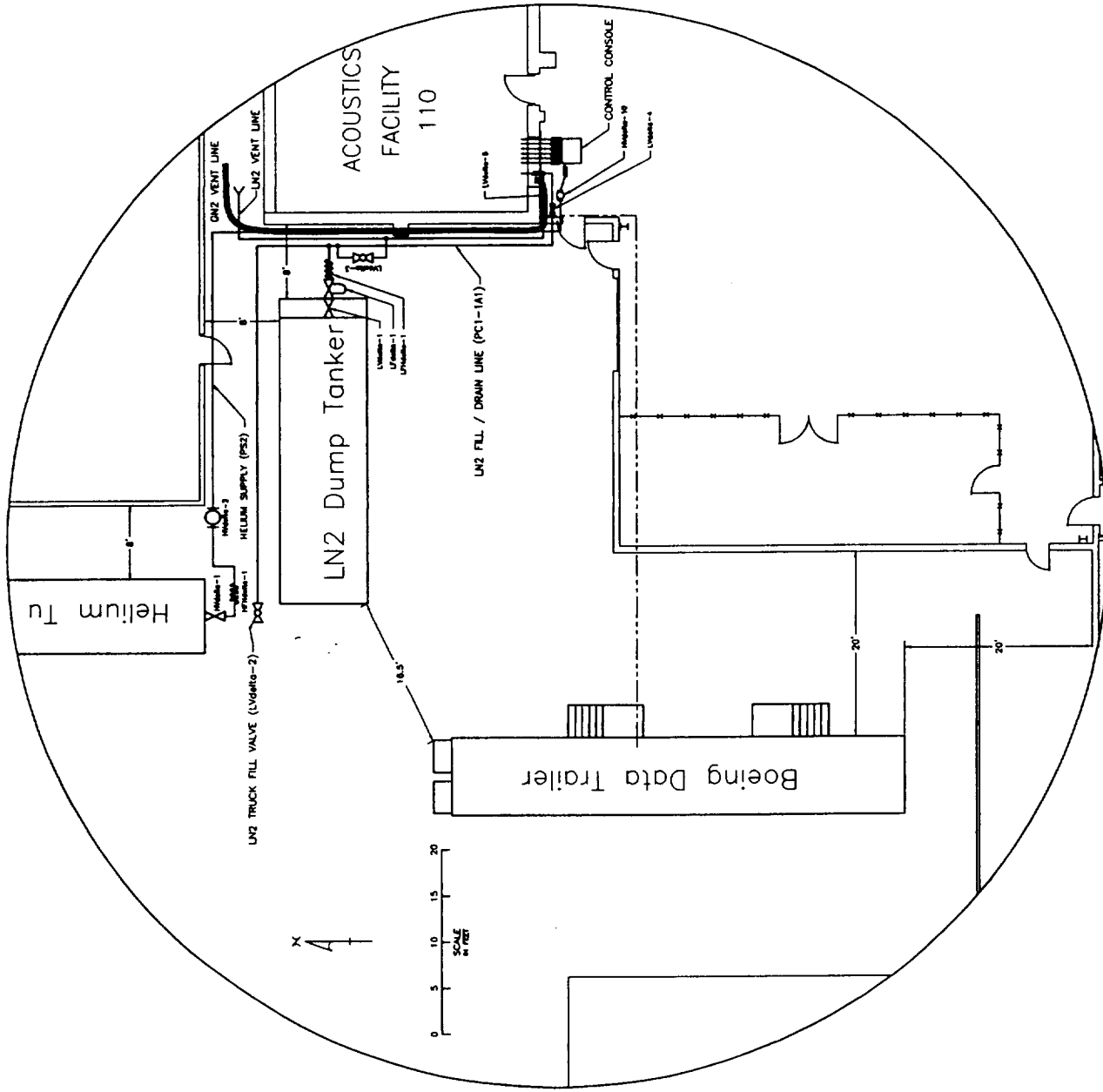


Figure 2: General Test Configuration

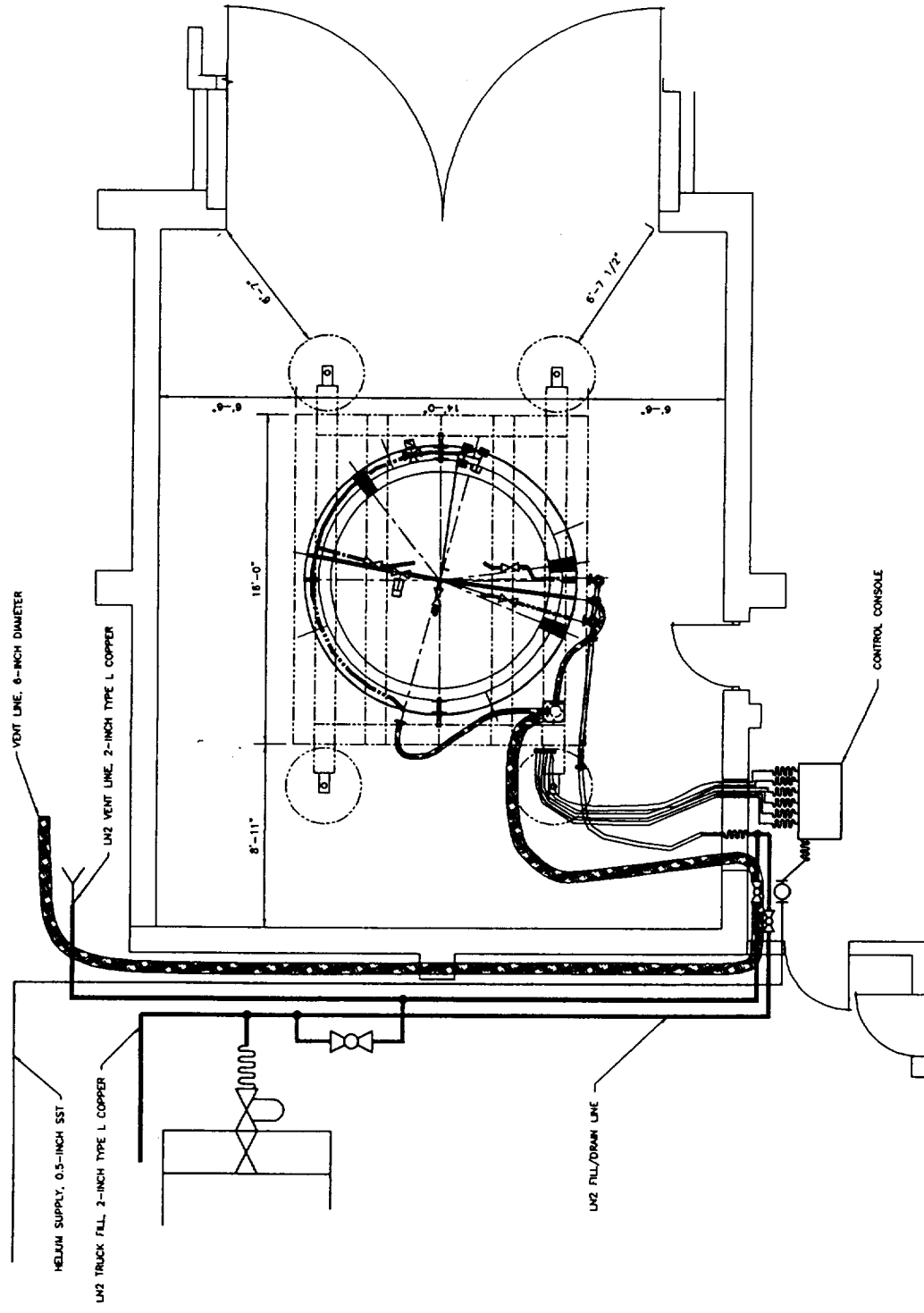


Figure 3: Plan View of the Piping Configuration in the Acoustic Test Cell

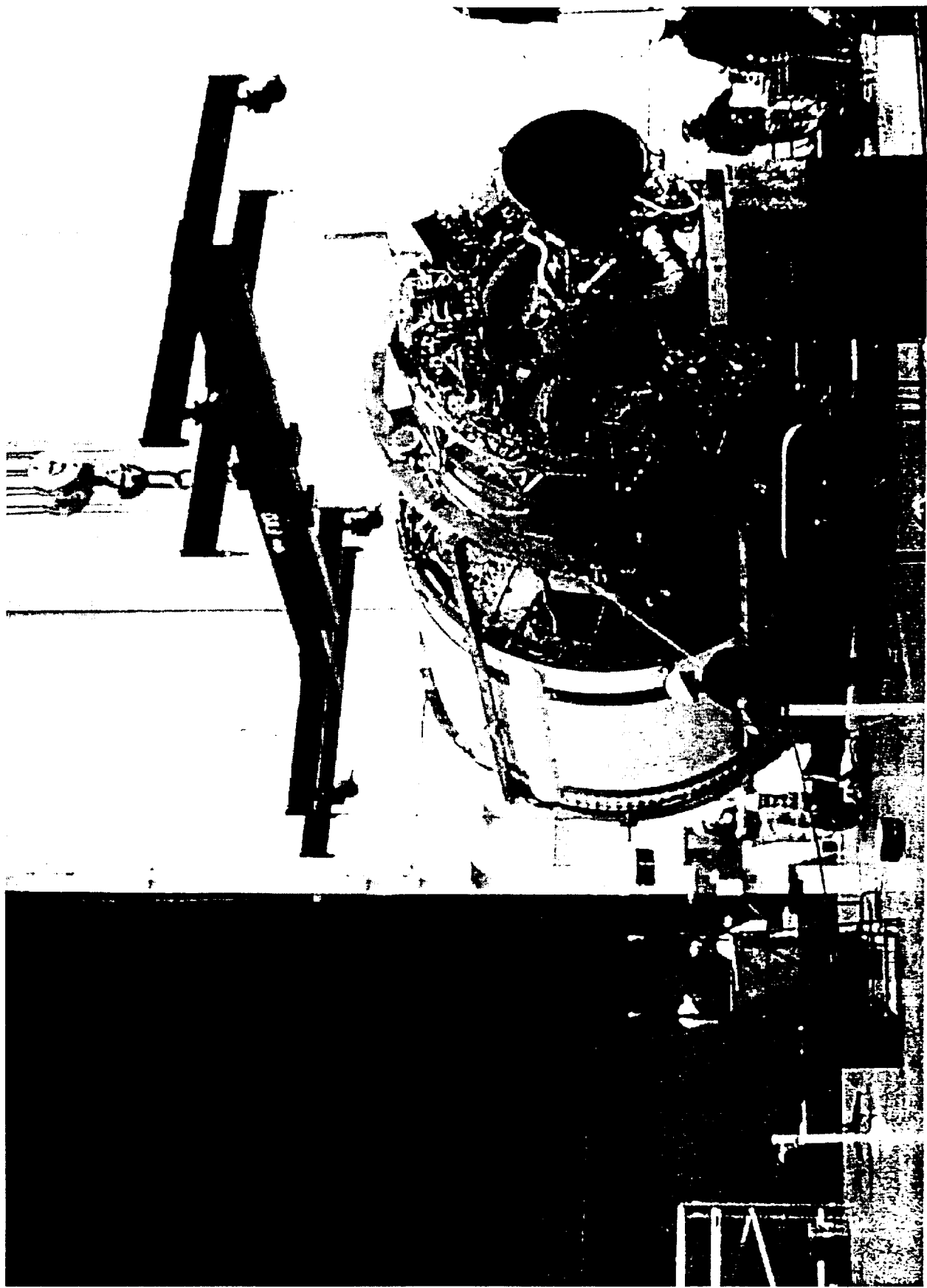


Figure 5: Delta III Second Stage After Arrival at Goddard Space Flight Center

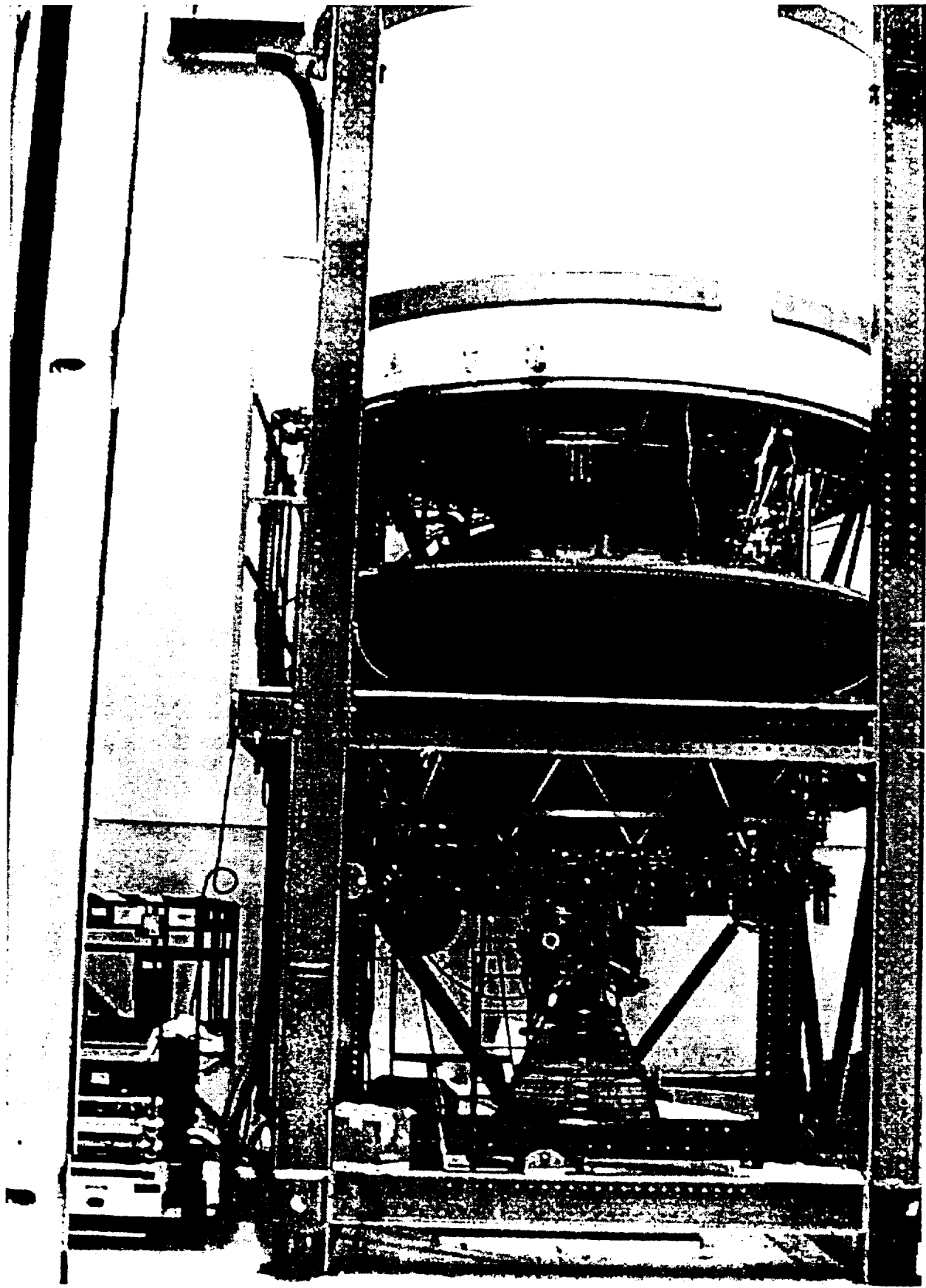


Figure 6: Delta III Second Stage and Mobile Support Fixture Configured in the Acoustic Cell


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